Are Active Galactic Nuclei the Solution to the Excess Cosmic Radio Background at 1.4 GHz?

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ABSTRACT

Recently the ARCADE 2 experiment measured the cosmic radio background (CRB) and found the brightness temperature of the CRB at 1.4 GHz to be ∼480 mK. Integrating the flux density from the observed 1.4 GHz radio source count produces a brightness temperature of ∼100 mK—less than a quarter of the observed CRB at 1.4 GHz. Radio quiet AGN are a large fraction of the 1.4 GHz μJy sources and typically host significant star formation. Thus, it is possible that AGN and host star formation could be responsible for some fraction of the excess CRB at 1.4 GHz. Here, an X-ray background population synthesis model is used in conjunction with empirical radio to X-ray luminosity ratios to calculate the AGN contribution to the CRB at 1.4 GHz including the emission from host star formation. It is found that AGN and host star formation contribute $\lesssim$9% of the CRB at 1.4 GHz. When all known 1.4 GHz radio source classes are considered, $\lesssim$60% of the CRB at 1.4 GHz is accounted for; therefore, it is necessary that either known radio sources evolve significantly at flux densities below current survey sensitivity limits or a new population of low flux density radio sources exist.

Subject headings: galaxies: active — galaxies: Seyfert — quasars: general — galaxies: starburst — radio continuum: galaxies

1. Introduction

Extragalactic backgrounds are important tools in understanding the density and evolution of different objects within the universe. The γ-ray background places constraints on dark matter annihilation (e.g., Cirelli et al. 2010), the X-ray background (XRB) provides a

census of accretion onto supermassive black holes (e.g., Gilli et al. 2007), the cosmic infrared background (CIRB) encodes the history of obscured star formation and galaxy evolution (e.g., Lutz et al. 2011), and the cosmic microwave background (CMB) provides the deepest insights into the early universe (e.g., Komatsu et al. 2011). It is known that at least two source populations contribute to the cosmic radio background (CRB). At fluxes > 1 mJy radio loud active galactic nuclei (AGN), actively accreting supermassive black holes defined by $f_5/f_B \gtrsim 10$, where f_5 is the 5 GHz flux density and f_B is the B band flux density (Kellermann et al. 1989), are the dominate source population (e.g., Windhorst et al. 1993). At lower flux densities, the 1.4 GHz source count steepens as star forming galaxies (SFGs) and radio quiet AGN begin to dominate. Recently, the ARCADE 2 experiment measured the CRB at frequencies between 3 and 90 GHz and found that the spectrum of the observed CRB suggests that the extragalactic brightness temperature at 1.4 GHz is $\sim$480 mK (Fixsen et al. 2011, their eq. 6). Even when considering the large dispersion between various observed source counts, extrapolating the total observed source count at 1.4 GHz to lower flux densities can only account for $\sim$100 mK of the observed CRB (Gervasi et al. 2008; Seiffert et al. 2011; Vernstrom et al. 2011). The next step must be to consider phenomenological models of individual source classes. Here, the contribution of AGN and their hosts to the CRB is investigated.

Radio quiet AGN, although less radio luminous, are much more common than radio loud AGN, and thus are an important class of sources in the μJy flux density range at 1.4 GHz (e.g., Padovani et al. 2009). Furthermore, radio quiet AGN host galaxies are known to host significant star formation (e.g., Lutz et al. 2010; Yuan et al. 2010). Therefore, it is plausible that emission from radio quiet AGN and their hosts makes a significant contribution to the CRB at 1.4 GHz. Using optical AGN luminosity functions, Singal et al. (2010) find that radio quiet AGN should contribute a few percent of the CRB. While optical AGN luminosity functions do include emission from the host galaxy (Draper & Ballantyne 2011b), star formation in AGN hosts tends to be obscured (e.g., Lutz et al. 2010); therefore, AGN host star formation contributes very little to the total optical luminosity of the AGN system. Star formation in AGN hosts must be carefully considered in order to understand the possible range of CRB fractions which can be accounted for by AGN system radio emission.

Here, a detailed accounting of the AGN contribution to the CRB is conducted with the inclusion of star formation in AGN host galaxies. The framework of XRB population synthesis modeling is combined with empirical X-ray to radio flux ratios. This allows for the consideration of AGN with radio flux densities well below the current survey sensitivity limits. Variations in the AGN contribution to the CRB due to uncertainty in the evolution of AGN host star formation, the AGN luminosity function, and the AGN radio to X-ray luminosity ratio are also explored. A Λ-dominated cosmology is assumed with $h = 0.7$, and

$\Omega_\Lambda = 1 - \Omega_m = 0.7$ (Spergel et al. 2003). Radio sources have a flux density with spectral index α, such that $S \propto \nu^\alpha$.

2. Calculations

The AGN number counts at 1.4 GHz are calculated between S_{max} = 10 mJy and S_{min} = 100 nJy, in the same manner as by Ballantyne (2009). An XRB synthesis model is used to characterize the space density of AGN, the AGN type 2/type 1 ratio, f_2, and the fraction of Compton thick (CT) AGN, f_{CT} (e.g., Ballantyne et al. 2006; Draper & Ballantyne 2009), AGN with obscuring column densities $N_H > 10^{24}$ cm^{-2}. Either the Ueda et al. (2003) or La Franca et al. (2005) hard X-ray luminosity function (HXLF) is used to model the space density and evolution of AGN. The evolution of f_2 is dependent on both L_X, the AGN 2–10 keV luminosity, and redshift, z, in the manner determined by Ballantyne et al. (2006). The f_{CT} is determined by fitting the peak of the XRB at $\sim$ 30 keV and the local space density of CT AGN (Draper & Ballantyne 2010; Ballantyne et al. 2011). Both the scenario where CT AGN evolve like less highly obscured type 2 AGN ($10^{22} < N_H < 10^{24}$ cm^{-2}) and the scenario where CT AGN are in specific evolutionary states are considered (see Draper & Ballantyne 2010).

Following Terashima & Wilson (2003), the ratio of 5 GHz radio luminosity to L_X for radio quiet AGN, defined as $R_X \equiv \log(\nu L_\nu(5GHz)/L_X)$ is characterized as

$$R_X = \begin{cases} -0.67\log L_X + 23.67 & 41.5 \le \log L_X \le 43 \\ -5 & 43 < \log L_X \le 44 \\ \log L_X - 49 & 44 < \log L_X \le 45 \\ -4 & \log L_X > 45. \end{cases} \tag{1}$$

The AGN 5 GHz luminosity is converted to 1.4 GHz using a spectral index of α = -0.7[1] (Kukula et al. 1998). Ballantyne (2009) showed that the radio quiet AGN R_X relation of Panessa et al. (2007) is also consistent with the current observed AGN radio number counts. The Panessa et al. (2007) radio quiet R_X, based on observations of local Seyferts, is nearly constant with luminosity. Radio loud AGN X-ray luminosities are converted to radio luminosities using the relation

$$R_X \approx -2.0 \tag{2}$$

[1]If the α distribution for radio quiet AGN observed by Kukula et al. (1998) is approximated as Gaussian with $\bar{\alpha}$ = -0.7 and σ = 0.6, the radio quiet AGN contribution to the brightness temperature increases by $<$ 1 mK.

(Terashima & Wilson 2003). For the radio loud AGN a spectral index of α = -0.8[2] is used to convert from 5 GHz to 1.4 GHz luminosity.

The HXLF contains both radio quiet and radio loud AGN. In order to separate the radio quiet AGN and the radio loud AGN, a radio loud fraction, f_{RL}, must be defined. Ballantyne (2009) found that radio number counts between 1 and 10 mJy were well fit assuming an exponential increase from $f_{RL} = 0.0175$ at $\log L_X = 41.5$ to $f_{RL} = 0.10$ at $\log L_X \geq 46.0$, at all z. This is consistent with the overall radio loud fraction being 0.1-0.2 (e.g., Donoso et al. 2009).

It is well documented that galaxies hosting AGN also tend to host on-going star formation (Draper & Ballantyne 2011a, and references therein), thus the radio flux density due to star formation within AGN host galaxies must be considered for an accurate calculation of the AGN radio number counts. The Bell (2003) calibration is used to convert a star formation rate (SFR) into a 1.4 GHz radio luminosity assuming that the infrared-radio correlation (IRC) does not evolve with z. For the radio spectrum of star forming regions, α = -0.8 is assumed (Yun et al. 2001). The 1.4 GHz radio differential number counts, dN/dS, are then calculated as in Equation 2 of Ballantyne (2009).

Once dN/dS is known, calculation of the brightness temperature, $T(\nu)$, is straight forward. The intensity $I(\nu)$ is related to dN/dS such that

$$I(\nu) = \int_{S_{min}}^{S_{max}} \frac{dN}{dS}(\nu) \cdot S dS. \tag{3}$$

The Rayleigh-Jeans approximation gives

$$T(\nu) = I(\nu)\frac{\lambda^2}{2k}, \tag{4}$$

where λ = 21 cm is the wavelength and k is the Boltzmann constant. Thus, by applying the machinery of the XRB and using empirically determined conversions between X-ray and radio luminosities, the AGN contribution to the 1.4 GHz CRB is calculated.

With the basic model in place, the contribution of AGN systems to the CRB is investigated. The results from the Ueda et al. (2003) and La Franca et al. (2005) HXLFs and the Terashima & Wilson (2003) and Panessa et al. (2007) radio quiet R_X relations are compared. Constant and evolving star formation laws are explored. Both an evolving and non-evolving

[2]If the α distribution for radio loud AGN observed by Lin & Mohr (2007) is approximated as Gaussian with $\bar{\alpha}$ = -0.8 and σ = 0.6, the radio loud AGN contribution to the brightness temperature decreases by $<$ 0.5 mK.

model of f_{CT} are considered. Analyzing such a large portion of the parameter space allows the maximum possible contribution to the CRB from AGN to be determined. The resulting models are then constrained by the observed 1.4 GHz number counts.

3. Results

3.1. Bare AGN

First, the host star formation is ignored and the contribution to the CRB from bare AGNs is considered and shown in the upper part of Table 1. The listed χ^2_{red} values refer to the 15 AGN data points from Seymour et al. (2008) and Padovani et al. (2011) shown as the red, blue, and cyan data in Figure 1. The Panessa et al. (2007) R_X predicts an AGN brightness temperature ∼5 mK higher than the Terashima & Wilson (2003) R_X. Similarly, the La Franca et al. (2005) HXLF produces an AGN brightness temperature ∼5 mK higher than the brightness temperature predicted by the Ueda et al. (2003) HXLF. The blue lines in Figure 1 show the Euclidean normalized 1.4 GHz differential number counts for the bare AGN model with the lowest χ^2_{red}, which assumes the La Franca et al. (2005) HXLF and the Panessa et al. (2007) R_X. Thus, bare AGN appear to only contribute ∼4% of the CRB at 1.4 GHz, in agreement with the results of Singal et al. (2010).

The minimum X-ray luminosity of the XRB framework is $L_X^{min} = 10^{41.5}$ erg s^{-1}, which corresponds to a minimum radio loud AGN 1.4 GHz radio luminosity of 1.8×10^{23} W Hz^{-1}. In the VLA-COSMOS survey, radio loud AGN were observed with 1.4 GHz radio luminosities down to $\sim 5 \times 10^{21}$ W Hz^{-1} (Smolčić et al. 2009). Therefore, the 1.4 GHz radio loud AGN luminosity function of Smolčić et al. (2009) is used to assess the importance of the low luminosity radio loud AGN. The radio loud AGN contribution to the CRB using both the pure density evolution (PDE) and pure luminosity evolution (PLE) versions of the Smolčić et al. (2009) luminosity function are shown in the fifth and sixth rows of Table 1. The dot-dashed line in Figure 2 shows the radio loud contribution to the differential number counts using the Smolčić et al. (2009) PDE luminosity function. As radio loud AGN are X-ray luminous for only a fraction of their lifetime (Draper & Ballantyne 2009), it is possible to assume that all X-ray selected AGN in the Ueda et al. (2003) HXLF are radio quiet AGN. In this case, bare AGN contribute ∼6–8% of the CRB at 1.4 GHz, depending on whether the PLE or PDE evolution is used for the radio loud luminosity function.

3.2. Accounting for Star Formation

It is known that AGN hosts have star formation (Draper & Ballantyne 2011a); thus, we now consider the effect of AGN host star formation on the AGN and host contribution to the CRB. Ballantyne (2009) found that if AGN have either SFR $\approx$ 2–3 $M_\odot$ yr^{-1} or

$$SFR \approx 0.25(1+z)^{1.76}(\log L_X - 40)^{3.5} M_\odot \; yr^{-1}, \tag{5}$$

the predicted number counts are in good agreement with observations, as shown by the black lines in Figure 1. However, as shown in the bottom half of Table 1, adding star formation to AGN hosts only increases the contribution of AGN and their hosts to the CRB by $\lesssim$10 mK.

We also consider the evolving CT AGN model of Draper & Ballantyne (2010), in which CT AGN have a physically motivated Eddington ratio distribution. This model is in agreement with the XRB, the local space density of CT AGN, and $z \sim 2$ mid-infrared estimations of the CT AGN space density (Draper & Ballantyne 2010). The third to last row in Table 1 shows the AGN contribution to the CRB using the evolving f_{CT} model and the evolving SFR of Ballantyne (2009). The evolving model is in better agreement with the observed number counts and results in a higher brightness temperature than the non-evolving model.

In order to evaluate the maximum possible contribution of AGN and their hosts to the CRB, it is assumed that AGN systems dominate the 1.4 GHz radio number counts down to the 10 μJy flux density level. For this scenario, the radio loud AGN are accounted for using the Smolčić et al. (2009) PDE luminosity function, and it is assumed that all AGN in the Ueda et al. (2003) HXLF are radio quiet. The evolving f_{CT} model is used and the radio quiet AGN hosts are assigned the SFR described in Equation 5. This maximal scenario is shown in Figure 2 and summarized in the last row of Table 1. Thus, it is clear that AGN contribute to the CRB; however, the maximum contribution to the CRB from AGN and their hosts, which is in reasonable agreement with the observed source count, as shown in Figure 2, is $\sim$42 mK, or $\sim$9%, of the CRB at 1.4 GHz. However, in the best fit model, as assessed by the minimum χ^2_{red}, AGN and their hosts contribute only $\sim$28 mK, or $\sim$6%, of the CRB at 1.4 GHz.

4. Discussion and Summary

We have shown that AGN systems contribute $\lesssim$9% of the CRB at 1.4 GHz. Thus the contribution of other source classes to the CRB must be considered. In Table 2 the known dominant source classes of the CRB are listed with the expected contribution of each source class.

It is known that star forming galaxies (SFGs) are an important source class in the μJy and nJy flux density ranges. Integrating the number counts predicted by the Padovani et al. (2011) 1.4 GHz SFG luminosity function suggests that SFG only contribute $\sim$3% of the CRB at 1.4 GHz. However, current surveys do not reach radio flux densities < 10 μJy; thus the best estimates of the contribution of SFGs to the CRB, which do not require extrapolation of the observed source counts, are computed using the IRC and the CIRB. If the IRC does not evolve with z and maintains the locally observed correlation at high z, then SFGs only contribute $\sim$9% of the CRB at 1.4 GHz (Ponente et al. 2011). It is unclear whether the IRC evolves with z or not, however, Ponente et al. (2011) find that if the IRC evolves with z in a manner which is consistent with current observations, SFGs still only contribute $\sim$14% of the CRB at 1.4 GHz. It is possible that low power, high redshift AGN systems, which observationally would be difficult to distinguish from SFGs, may increase this percentage (Singal et al. 2010).

As AGN, based on the calculation presented here, and SFGs, based on estimations from the IRC, can account for only $\sim$25% of the CRB at 1.4 GHz, additional low flux density source classes must be considered. One possible source class is radio supernovae (RSNe), however, these objects are short-lived and not common enough to make a significant contribution to the CRB (Singal et al. 2010). Padovani (2011) suggests that low radio power ellipticals (LRPEs) and dwarf galaxies may be important source classes at flux densities currently below survey sensitivities. LRPEs are predicted to have similar surface densities as AGN, and thus are not a dominate contributor to the CRB. Dwarf galaxies are expected to dominate the source count at nJy flux densities, but Padovani (2011) predicts that dwarf galaxies will only contribute $\lesssim$8% of the CRB. Furthermore, Seiffert et al. (2011) point out that for a population of sub-mJy point sources to account for the difference between the observed CRB and the brightness temperature predicted from the observed source count, the surface density of this population must exceed the surface density of galaxies in the Hubble Ultra Deep Field (Beckwith et al. 2006). Therefore, it is likely that the unaccounted for CRB is due to the evolution of known sources or an evolution of processes, such as those responsible for the IRC, and not due to an unknown source class.

Despite the current lack of a dominant candidate point source class, it is unlikely the 1.4 GHz CRB is dominated by diffuse sources. Singal et al. (2010) considers the contribution from low-surface-brightness sources. Sources which may emit a large flux over an extended area may have low enough surface brightness to be missed by current survey source counts. Singal et al. (2010) finds that the low-surface-brightness sources can at most contribute $\sim$25% of the CRB. Furthermore, the constraints placed on the CRB from the XRB and γ-ray background are inconsistent with the CRB being dominated by diffuse emission from a population of relativistic electrons within the intracluster medium or intergalactic medium

(Singal et al. 2010; Lacki 2011). Thus, other sub-μJy sources must be considered in order to fully account for the CRB at 1.4 GHz.

In conclusion, a detailed accounting of the AGN and host star formation contribution to the CRB has been carried out using the constraints of XRB population synthesis modeling and empirical X-ray to radio AGN luminosity ratios. This study has shown that AGN and host star formation contribute $\lesssim$9% of the CRB at 1.4 GHz. In a best case scenario, all sources currently considered in the literature contribute $\lesssim$60% of the CRB at 1.4 GHz. The unaccounted for radio emission must come from either a new low flux density radio population or from a known radio population with a strong evolution of the radio emission for low flux density objects. Therefore, it is necessary that radio surveys continue to explore the radio source count down to sub-μJy levels in order to resolve the source class responsible for the unaccounted for CRB flux density at 1.4 GHz.

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Table 1. Contribution of AGN to the 1.4 GHz CRB

HXLF	Star Formation Law	T_{total} (K)	T_{RL} (K)	χ^2_{red}
	Bare AGN			
U03	-	0.013	0.011	8.3
U03[a]	-	0.019	0.011	1.0
LF05	-	0.018	0.015	4.1
LF05[a]	-	0.023	0.015	0.6
S09 PDE + U03[b]	-	0.033	0.031	7.6
S09 PLE + U03[b]	-	0.023	0.021	1.7
	AGN + Star Formation			
U03	SFR = 3 $M_\odot$ yr^{-1}	0.021	0.011	1.5
LF05[a]	SFR = 2 $M_\odot$ yr^{-1}	0.028	0.015	1.3
U03	Eq. 5	0.019	0.011	1.9
LF05	Eq. 5	0.028	0.015	0.4
U03[c]	Eq. 5	0.024	0.014	0.9
U03[c]	Eq. 5[d]	0.029	0.014	5.5
S09 PDE + U03[b,c]	Eq. 5	0.042	0.031	19

[a]Radio quiet AGN L_X is converted to radio luminosity using the Panessa et al. (2007) conversion. For all other models the radio quiet L_X is converted to radio luminosity using Equation 1.

[b]Radio loud AGN are accounted for using the Smolčić et al. (2009) 1.4 GHz radio luminosity function for radio loud AGN which is evolved using either pure density evolution (PDE) or pure luminosity evolution (PLE). The radio quiet AGN are modeled using the Ueda et al. (2003) HXLF assuming that all X-ray AGN are radio quiet.

[c]Uses the evolving f_{CT} model of Draper & Ballantyne (2010)

[d]Star formation follows the functional form of equation 5 with a different normalization factor. Compton thin AGN have normalization factor 0.3 while low Eddington ratio CT AGN have normalization factor 0.05 and high Eddington ratio CT AGN have normalization factor 4.0

Note. — U03 refers to Ueda et al. (2003), LF05 refers to La Franca et al. (2005), and S09 refers to Smolčić et al. (2009). T_{RL} is the brightness temperature of radio loud AGN.

Table 2. Contributions of various sources to the 1.4 GHz CRB

		Brightness Temperature (K)	Reference
	Total Measured CRB	0.48 ± 0.07	Fixsen et al. (2011)
	AGN	0.018	this work
	AGN+SF	0.025	this work
(1)	Max AGN+SF	0.042	this work
	SFG	0.015[a]	this work
	SFG non-evolving IRC	0.040[b]	Ponente et al. (2011)
(2)	SFG evolving IRC	0.063[c]	Ponente et al. (2011)
(3)	RSNe	$\lesssim$ 0.00017	Singal et al. (2010)
(4)	LRPEs	0.010[d]	Padovani (2011)
(5)	Dwarf SFGs	0.038	Padovani (2011)
(6)	Low-surface-brightness Sources	0.120	Singal et al. (2010)
	Total (1–6)	0.27	

[a]Calculated by integrating the number counts predicted by the Padovani et al. (2011) observed SFG broken power law luminosity function at 1.4 GHz and assuming α = -0.8.

[b]Converted from 1 GHz using Eq. 19 and 20 of Ponente et al. (2011).

[c]Converted from 1 GHz using Eq. 19 and 21 of Ponente et al. (2011).

[d]Estimated based on the expectation that LRPEs have surface density and flux densities similar to radio quiet AGN.

Note. — SF refers to star formation, SFG refers to star forming galaxy, IRC refers to the infrared-radio correlation, RSNe refers to radio supernovae, and LRPE refers to low radio power ellipticals.

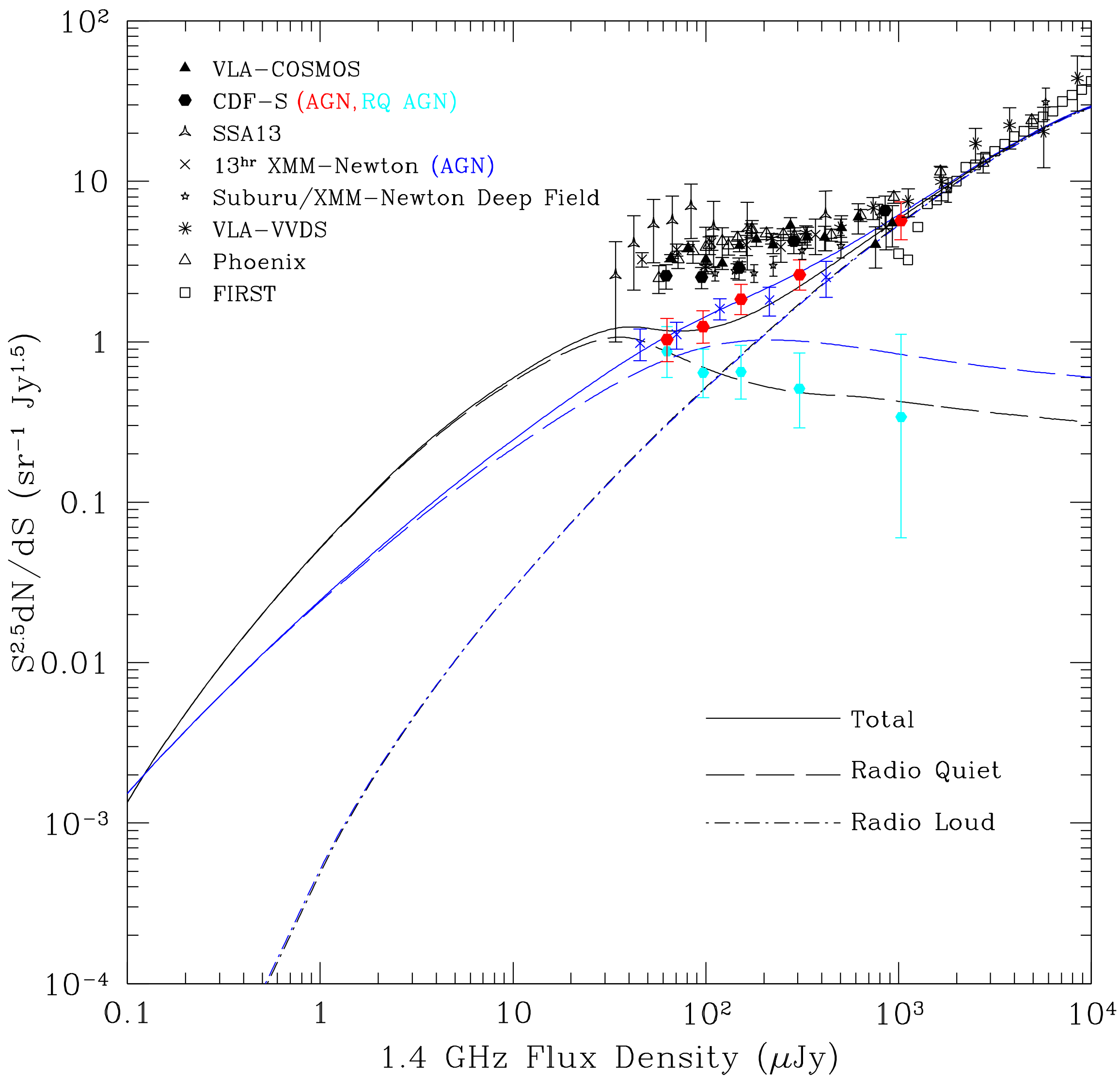

Fig. 1.— Euclidean normalized 1.4 GHz differential number counts for bare AGN and AGN with star formation. The blue lines show bare AGN assuming the La Franca et al. (2005) HXLF and Panessa et al. (2007) R_X, as summarized in the fourth line of Table 1. The black lines show AGN with host SFR as described by Equation 5, the La Franca et al. (2005) HXLF and the Terashima & Wilson (2003) R_X, as summarized in the tenth row of Table 1. Also shown are the observed source counts from a variety of surveys: VLA-COSMOS (Bondi et al. 2008), CDF-S (Kellermann et al. 2008), SSA 13 (Fomalont et al. 2006), 13 hr *XMM-Newton* (Seymour et al. 2004), Suburu/*XMM-Newton* Deep Field (Simpson et al. 2006), VLA-VVDS (Bondi et al. 2003), Phoenix (Hopkins et al. 2003), and FIRST (White et al. 1997). The blue and red points show the estimated AGN radio counts from the 13 hr *XMM-Newton* (blue; Seymour et al. 2008) and CDF-S (red; Padovani et al. 2011). The cyan points show the estimated radio quiet AGN 1.4 GHz counts in the CDF-S (Padovani et al. 2011).

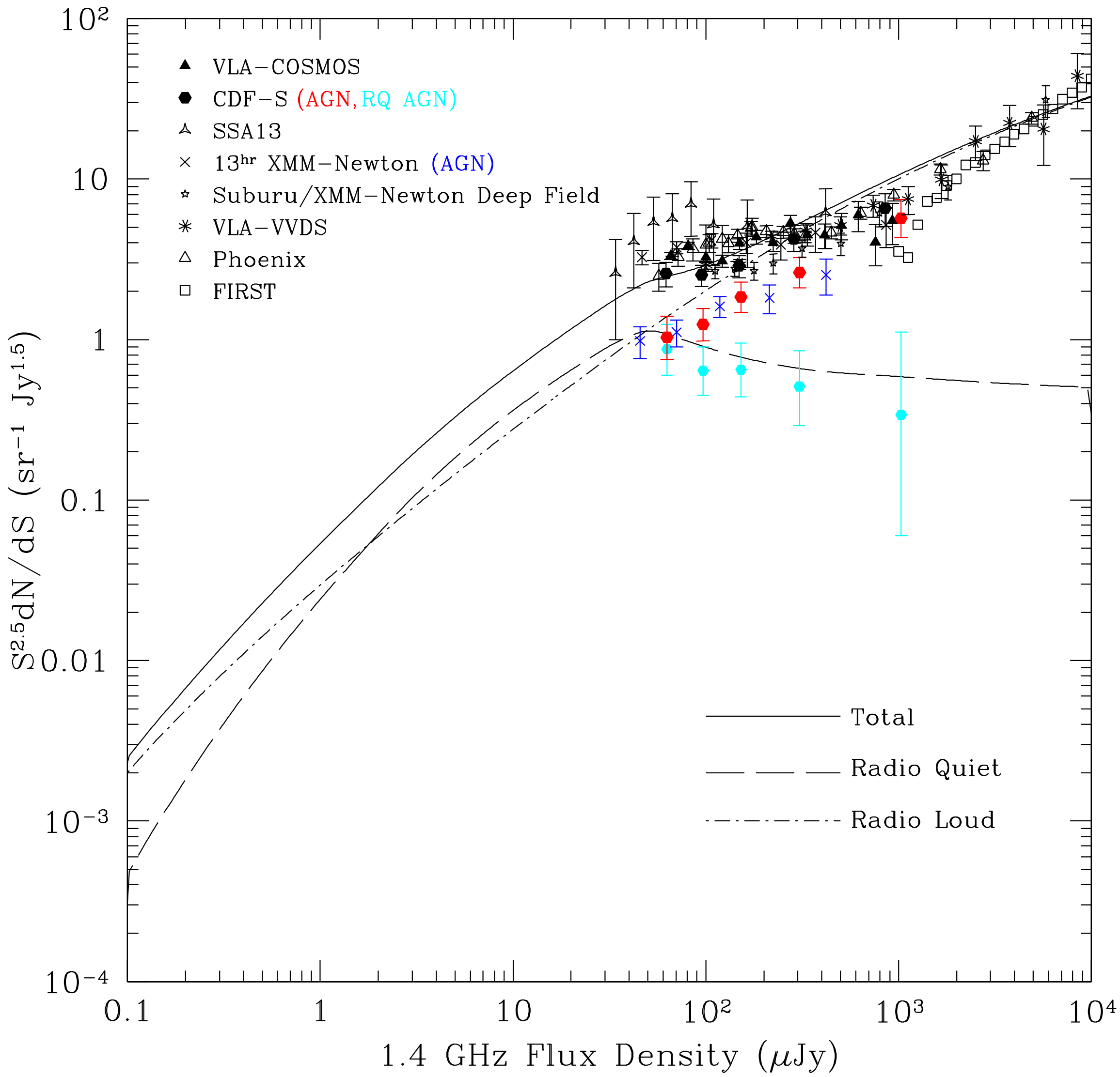

Fig. 2.— Euclidean normalized differential number counts for the maximal AGN and host star formation contribution to the 1.4 GHz CRB (last line of Table 1). The radio loud AGN are accounted for using the Smolčić et al. (2009) PDE luminosity function and the radio quiet AGN are accounted for using the Ueda et al. (2003) HXLF, the evolving f_{CT} model of Draper & Ballantyne (2010), and the Terashima & Wilson (2003) R_X. The SFR of the radio quiet AGN hosts is described by Equation 5. This model gives the maximal total AGN and host brightness temperature of 0.042 K. The plotted data is the same as in Figure 1.